

North Atlantic Oscillation primary productivity and toxic phytoplankton in the Gullmar Fjord, Sweden (1985–1996)

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The evaluation of the time-series data set of primary production, chlorophyll *a* (1985–1996) and toxic phytoplankton species abundance measurements (1986–1996) in the Gullmar Fjord as part of the Swedish Monitoring Program, revealed the importance of considering climatic and environmental forces among the factors that may be responsible for the observed fluctuations. The results suggested that the occurrence of toxic phytoplankton blooms in the Skagerrak may be related to changes in the phase of the North Atlantic Oscillation (NAO). The *Dinophysis* species were related to the NAO, temperature and salinity and the fluctuations in the phytoplankton biomass expressed as chlorophyll *a* were also shown to be related to the NAO. The results pointed to the need to understand further the role played by climatic and environmental forces in relation to the formation and duration of harmful algal blooms and the need for continuous quality monitoring programmes and novel statistical methods for detecting trends and cycles in ecological time-series related to environmental forces.

Keywords: North Atlantic Oscillation; phytoplankton; primary productivity

1. INTRODUCTION

Marine research has been carried out in the Gullmar Fjord and adjacent waters for more than 100 years. The present pelagic monitoring programme started in 1985 at the Kristineberg Marine Research Station. In 1988, due to the alarming bloom of *Chrysochromulina polyepsis* along the Swedish west coast, a high-frequency pelagic monitoring programme was funded by the Swedish Environmental Protection Agency. The pelagic ecosystem of the Gullmar Fjord has been studied since the late 1970s and special attention has been paid to the relationship between hydrodynamic processes in relation to the observed changes in both the zooplankton and phytoplankton community. Lindahl & Hernroth (1988) suggested the importance of considering the oceanographic variability in the Skagerrak area and the possible influence of climatic forces on long-term variations in the pelagic community of the Gullmar Fjord in more detail.

The North Atlantic Oscillation (NAO) can be regarded as the changes in the difference in atmospheric pressure between the Azores and Iceland. This climatic oscillation has a strong influence on the regime of the westerly winds across the North Atlantic resulting in changes in winter temperatures on both sides of the Atlantic (Kerr 1997). The NAO plays an important role in circulation and convection in the North Atlantic and may be responsible for the changes in intensity of the subpolar gyre and the flow of the North Atlantic Current (Dickson 1997). Taylor *et al.* (1998) and Taylor & Stephens (1998) showed the possible links between the circulation and weather patterns in the

North Atlantic with events in the equatorial Pacific and also the relationship between the position of the Gulf Stream and the intensity of the NAO.

The NAO forces on *Calanus finmarchicus* and *Calanus helgolandicus* in the eastern North Atlantic were recently discussed by Fromentin & Planque (1996), who suggested that the oscillations in the NAO can be reflected in the spatial and temporal distribution of these copepod species. Recently, phytoplankton changes using data from the Continuous Plankton Record (CPR) were described for two areas in the North Atlantic and for the central North Sea from 1948–1995 (Reid *et al.* 1998). In the Skagerrak an increase in phytoplankton biomass was found in the mid-1980s similar to the results obtained by Reid *et al.* (1998). The NAO could influence the primary production in the Gullmar Fjord since it has been shown to be related to the westerly winds, which in turn are related to nutrient availability and run-off (Lindahl *et al.* 1998). The aim of the present study was an evaluation of the 12-year, time-series data set of primary productivity and chlorophyll *a* and the 11-year, time-series data set of toxic phytoplankton species in relation to the NAO and environmental forces.

2. MATERIALS AND METHODS

(a) Study area and sampling

The study area (figure 1) was located along the Swedish west coast. The Gullmar Fjord is influenced by both the surface Baltic current running parallel to the coast and from the central Skagerrak water circulation pattern, resulting in an inflow along the Swedish coast of North Atlantic deep water and North Sea water regulated by different physical processes and climatic

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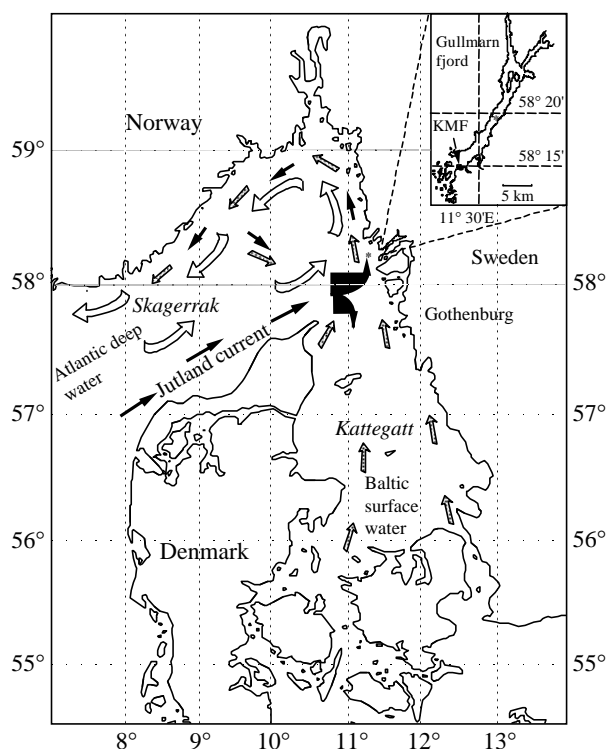


Figure 1. The Skagerrak and Kattegat area and the Gullmar Fjord. The sampling site (58° N, 11° E) corresponds to Kristineberg Marine Research Station (KMF) in the top right hand corner. The arrows are indicating the major currents system in the area.

forces (Rodhe 1987). The large bloom of *C. polyepsis* in 1988 clearly pointed out the importance of coastal currents for bloom formation, related to advection and hydrodynamic processes in the Skagerrak (Lindahl 1993).

The primary production time-series data set was collected monthly at Släggö during 1985–1996 at the mouth of the Gullmar Fjord just in front of the Kristineberg Marine Research Station (figure 1). The primary productivity was measured following the recommendations of the Baltic Marine Biologists (1976) by the ^{14}C technique *in situ* and integrated over a 0–20 m depth (Lindahl 1995). The phytoplankton were sampled monthly during 1986–1996 at Släggö, with a hose at the following integrated depths: 0–5, 5–10, 10–15 and 15–20 m. Samples were fixed using lugol (acid-iodine) with the exception for *C. polyepsis* and concentrated using sedimentation cylinders (10–50 ml) of combined plate chambers. Counting was carried out using an inverted microscope at three magnifications ($\times 10$, 20 and 40) with an ocular magnification of $\times 10$.

The counting procedure was carried out according to HELCOM (1988). The biovolume and carbon content were not estimated. In this study only the results of the regression analysis of three toxic *Dinophysis* species (*Dinophysis acuta*, *Dinophysis acuminata* and *Dinophysis norvegica*) in relation to the NAO, temperature and salinity are reported. These species were selected since they are regarded as the major toxic species present in the area and one of the most important species in harmful algal blooms (HABs) research. *Dinophysis* species are also responsible for the occurrence of diarrhetic shellfish toxin (DST) in the mussel *Mytilus edulis*, which is a farmed species in the Gullmar Fjord area, causing diarrhetic shellfish poisoning (DSP). *Dinophysis* are mixotrophic species (Jacobson &

Andersen 1994; Graneli *et al.* 1995) and their contribution to the total primary production is difficult to assess. In the Gullmar Fjord area their abundance can reach well over 10 000 cells per litre and this can be regarded as quite high compared, for example, with the abundance of *D. norvegica* and *D. acuminata* of 1500 cells per litre recorded in West Boothbay Harbor, Maine, US and reported by Jacobson & Andersen (1994). Copepods might be poisoned when *D. acuminata* constitutes a large portion of their diet with respect to other phytoplankton species (Graneli *et al.* 1995). Salinity, temperature and chlorophyll *a* were measured monthly with a conductivity temperature depth (CTD) probe (G.O. MARK IIIC) at hydrographic standard depths and analysed according to Swedish standard methods (SIS). The mean values of these variables were calculated to represent the conditions above and within or below the mean pycnocline depth: the surface water at 0–10 m and the subsurface water at 15–30 m.

(b) Statistical analysis

Time-series of monthly means of the NAO and yearly NAO winter index (December–March), sea surface temperature and primary production were analysed using Pearson correlations on both original and detrended series. Although the NAO primarily reflects the sea-level pressure condition during the winter months (Hurrell 1995) we wanted to extend our analysis by including the monthly means since in Scandinavia the winters are longer and summers shorter than other locations in Europe and the effect of the NAO may be extended for longer periods. The detrended series (original series minus polynomial trends) were used to detect correlations not due to long-term trends or to year-to-year fluctuations (Fromentin & Planque 1996). The primary production time-series decomposition was carried out according to Chatfield (1996). The significant correlation coefficients that remained after recomputing the correlation coefficients on the detrended series are reported. In order to take into account the presence of autocorrelation in the time-series the degrees of freedom were adjusted according to the method proposed by Bartlett (1946) and Priestly (1981). A Monte-Carlo approach (5000 simulations) was used to test the significance of the correlation as suggested by Prager & Hoenig (1989). Phytoplankton species were $\log(n+1)$ transformed in order to take account of the presence of zeros in the series. The species abundance counts at 0–5 m and 5–10 m depths were summed together to represent the species abundance above the pycnocline where most of the toxic phytoplankton tends to agglomerate. The species abundance at the subsurface depth layer (15–30 m) was not analysed since very low numbers were found. A stepwise linear regression analysis on the 0–10 m species data and chlorophyll *a* (0–10 m) was performed on the original series after removing the seasonal signal using a centred 12-month running mean (Reid *et al.* 1998). The coefficients of determination (R^2) for the toxic species are reported in table 2. To investigate the existence of lags between the NAO and the response in the primary production we used the specific population growth rate (R_t):

$$(R_t) = \ln(N_t/N_{t-\tau}),$$

where N_t is the population density at time t and $N_{t-\tau}$ is the population density at different lags, in this case the population density in the previous month. Primary production data were log transformed since this allows for having stationary time-series which are better when using linear methods (Royama

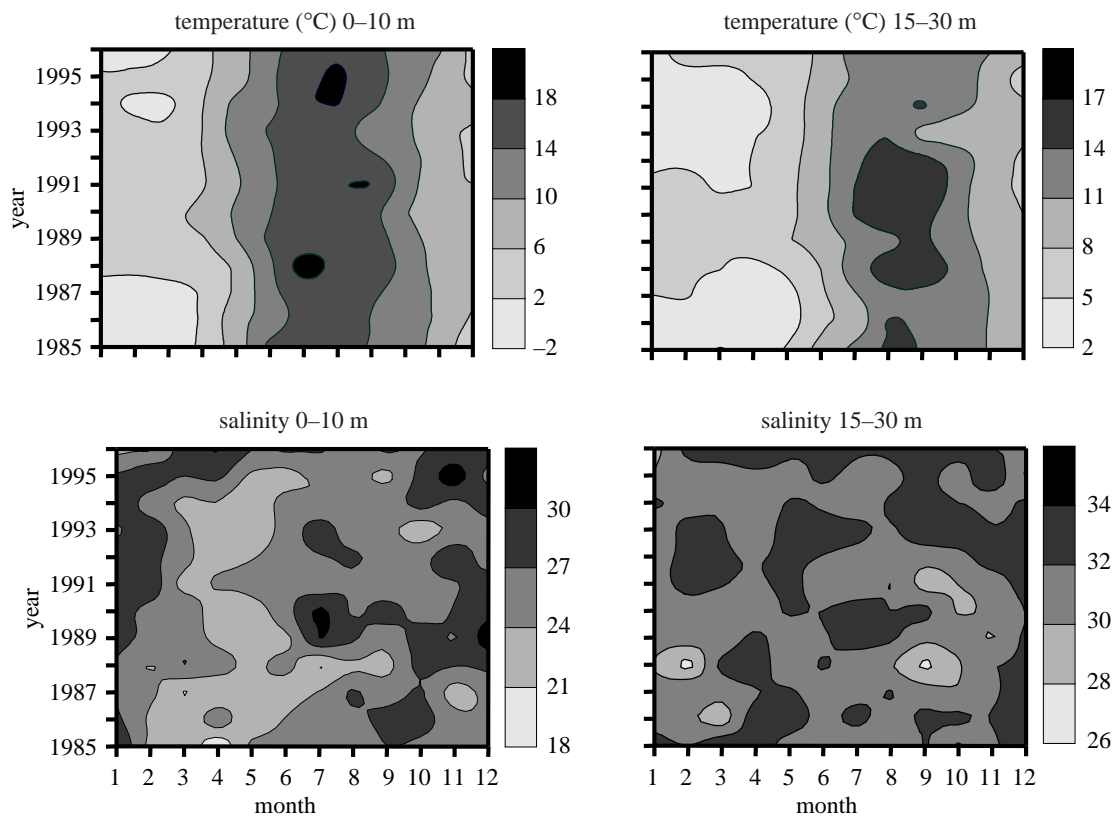


Figure 2. Temperature and salinity distribution expressed as monthly means during 1985–1996.

1992). The NAO was used as the independent variable at different lags. A cross-correlation function analysis was performed to identify lags in correlation between R_t and the NAO. The significance of the lags was reported by the coefficient of partial correlation by using a multiple linear stepwise regression analysis. The independent variable was entered in the model according to Neter *et al.* (1990) and the degrees of freedom were adjusted for autocorrelation according to Bartlett (1946) and Priestly (1981).

3. RESULTS

The temperature distribution (figure 2), showed the presence of a warmer period during the late 1980s for both surface and subsurface measurements concomitant with a positive phase of the NAO bringing warmer winters over Scandinavia. The salinity distribution (figure 2), for the same period showed an increased distribution of more saline surface water during winter and early spring, while in the subsurface layer a similar salinity was found in 1988 during winter and late summer. The temperature and salinity distribution over the 12-year period showed a highly stratified water body at the Gullmar Fjord. This pointed out that the coupling of climatic and physical processes need further attention in relation to the biological processes such as phytoplankton bloom formation, as reported by Lindahl & Hernroth (1983).

The primary production time-series (figure 3) is presented as the adjusted series after removing the seasonal component and the remaining smoothed trend

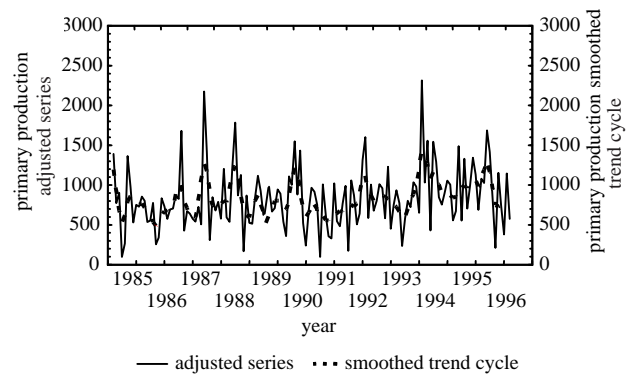


Figure 3. Daily mean primary production ($\text{mgC m}^{-2} \text{d}^{-1}$) for each month presented as an adjusted series after removing the seasonal effect on the left axis and the remaining smoothed trend on the right axis.

cycle. These preliminary results showed the oscillation patterns present in the data and, in particular, three periods of high primary production were observed during 1987–1988, in 1990 and in 1994. Periods of lower primary production was observed in 1989 and during 1991–1993. In order to verify the possible link between the primary production signal at the Gullmar Fjord and the NAO, the correlation analysis between sea surface temperature (SST), the NAO winter index (NAOWI) and May primary productivity are reported in table 1. The NAOWI and May primary production are presented in figure 4, to show that the NAOWI index may be influencing the primary productivity in the following month of May. The

Table 1. Pearson correlation coefficients on *NAOWI* and *SST* (0–10 m), and on *NAOWI* and May primary production (*PP*) for the Gullmar Fjord time-series (1985–1996) were tested by a Monte-Carlo approach (5000 simulations)

(Significant correlations were found at *** $p < 0.001$, ** $p < 0.01$ and * $p < 0.05$.)

NAO	correlation values, r
NAOWI and SST February	0.8462***
NAOWI and SST March	0.7692**
NAOWI and May PP	0.5664*

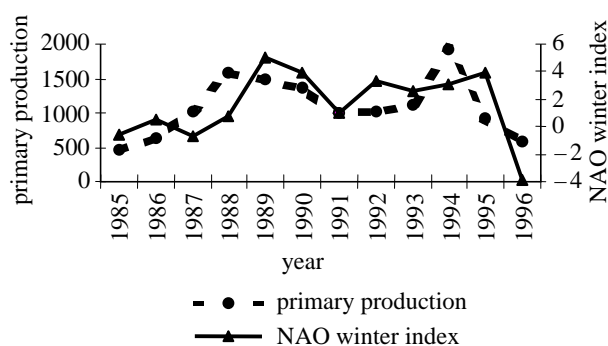


Figure 4. May daily mean primary production ($\text{mgC m}^{-2} \text{d}^{-1}$) and NAO winter index 1985–1996.

only significant correlations between the *NAOWI* and *SST* were found during February and March as an indication that changes in the NAO can be reflected in changes of the *SST* structure. The *NAOWI* was also correlated with the primary production in May as a possible indication that the occurrence of the phytoplankton blooms can be connected with climatic events occurring during the winter months in the North Atlantic.

The results of the cross-correlation analysis showed that the primary production was correlated with the NAO ($r = 0.6894$ and $p < 0.001$) with a lag of three months and the partial correlation coefficient (partial $r = 0.6573$ and $p < 0.001$) identified by the stepwise multiple linear regression analysis also supported this relationship. Furthermore, more than 60% of the variance in R_t was explained by the NAO lagging by three months ($R^2 = 0.63$ and $p < 0.001$). This was a further indication that the NAO can be regarded as a potential climatic force behind the primary production signal. The positive correlation ($r = 0.87$ and $p < 0.001$) and the result of the regression analysis ($R^2 = 0.76$ and $p < 0.001$) suggested that the observed fluctuations in the phytoplankton biomass distribution may also be related to changes in the NAO. From the mid-1980s and in particular in 1988 (figure 5) large phytoplankton blooms were recorded along the Swedish coast. The main species contributing to the blooms in 1988 were the toxic flagellate *C. polyepsis* and the dinoflagellate *Gyrodinium aureolum* which can also be regarded as a potential toxic species. These blooms coincided with a positive phase of the NAO index resulting in mild winters over Scandinavia and northern Europe, similar to the switch in the phytoplankton biomass in the North Atlantic reported by Reid *et al.* (1998).

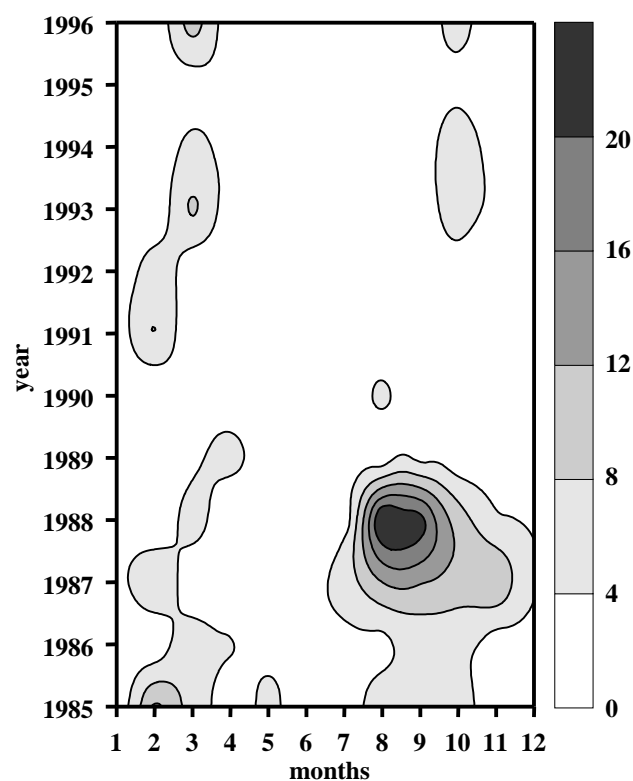


Figure 5. Phytoplankton biomass distribution expressed as chlorophyll *a* ($\mu\text{g l}^{-1}$) integrated over depth (0–10 m) from 1985 to 1996 at the mouth of the Gullmar Fjord in the Skagerrak.

Table 2. The coefficient of determination R^2 for the three *Dinophysis* species in relation to NAO, salinity (0–10 m) and temperature (0–10 m) for the Gullmar Fjord time-series (1986–1996)

(All the results are significant at $p < 0.001$.)

	NAO	salinity	temperature
<i>D. acuta</i>	0.949	0.857	0.653
<i>D. acuminata</i>	0.901	0.817	0.665
<i>D. norvegica</i>	0.890	0.814	0.669

4. DISCUSSION

The bottom water of the Skagerrak is replaced either by occasional inflows of deep water from the Norwegian Sea or by cooling of the water from the North Sea. Since warm weather conditions and low water exchange in the deep water coincide (Rodhe 1987), it is possible that a more stable stratification situation occurs in the Skagerrak during these periods allowing possible favourable conditions for the formation of toxic phytoplankton blooms.

The results of the linear regression analysis between the three *Dinophysis* species, NAO, temperature and salinity are presented in table 2. There was an indication that higher densities of toxic phytoplankton species may be associated with the positive oscillations of the NAO as, for example, during the late 1980s as well as warmer *SST* conditions and increased surface salinity and, on average, 80% of the variance was explained by the changes in

salinity and 90% by the NAO itself. Temperature explained *ca.* 65% of the variance. Salinity and temperature are also related to the NAO (Lindahl *et al.* 1998) but it was important to show how much of the variance could be explained separately by these different external forces. This is relevant information since good predictive models are often based on only a few exogenous variables (Turchin 1993). As discussed by Lindahl (1993), the distribution pattern of phytoplankton blooms along the Swedish coast suggested that offshore conditions in association with increased surface salinity are considered more favourable for the formation of toxic blooms than onshore conditions.

These observations on *Dinophysis* further confirmed and extended the hypothesis proposed by Lindahl (1993) that the observed phytoplankton blooms in the inshore waters may be the result of entrainment and advection of the surface population from offshore. As stressed in Danielssen *et al.* (1997) both the temporal and spatial distribution of phytoplankton in the Skagerrak may be related to the variability in the inflow of nutrient-rich Atlantic water. These preliminary results suggested the importance of studying the pattern of climatic oscillations such as the NAO in more detail (Hurrell 1995) and carrying out reanalysis of historical data. As pointed out by Lindahl & Hernroth (1983) these observations may be regarded as a result of a large-scale geographical phenomenon linked to climatic changes in accordance with the studies by Cushing & Dickson (1976), Colebrook (1978), Colebrook & Coombs (1978), Reid (1978) and Dickson *et al.* (1975). Climate changes in the North Atlantic during the past 30 years may be one of the causes of the observed changes in the phytoplankton abundance. The results draw attention to the importance of trying to relate climatic forces on pelagic biological systems and, in particular, in relation to outbreaks of toxic phytoplankton blooms in coastal areas (Vitousek *et al.* 1997) and on the oceanic variability in the Skagerrak (Danielssen *et al.* 1997).

Further modelling using nonlinear, non-parametric statistical methods (Ellner *et al.* 1998) is part of this ongoing research study for a better understanding of the mechanisms underlying these associations. These methods will allow us to take into account both endogenous and exogenous dynamic factors (Turchin 1993) present in the primary production and phytoplankton signals. These results were an indication of the possible direct and indirect links between changes in the patterns of the NAO and the response of physical and biological processes to climatic forces with particular emphasis on toxic phytoplankton species and the occurrence of toxic blooms.

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